Guest lecture Wednesday

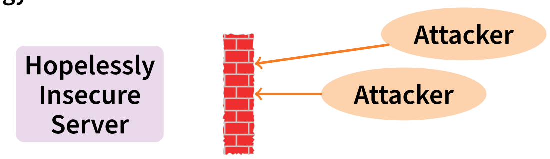
- **Please show up for guest lecture**
  - Hear about OS scheduling work happening at Google
- **There *will* be homework based on the guest lecture**

Outline

1. Confining code with legacy OSes
2. Virtual machines
3. Implementing virtual machines
4. Binary translation
5. Hardware-assisted virtualization
6. Memory management optimizations

Confining code with legacy OSes

- **Often want to confine code on legacy OSes**
- **Analogy: Firewalls**



  - Your machine runs hopelessly insecure software
  - Can't fix it—no source or too complicated
  - *Can* reason about network traffic
- **Can we similarly block untrusted code *within* a machine**
  - Have OS limit what the code can interact with

Using chroot

- `chroot (char *dir)` **"changes root directory"**
  - Kernel stores root directory of each process
  - File name "`/`" now refers to `dir`
  - Accessing "`..`" in `dir` now returns `dir`
- **Need root privileges to call chroot**
  - But subsequently can drop privileges
- **Ideally "Chrooted process" wouldn't affect parts of the system outside of `dir`**
  - Even process still running as root shouldn't escape chroot
- **In reality, many ways to cause damage outside `dir`**

Escaping chroot

- **Re-chroot to a lower directory, then chroot `../../..`**
  - Each process has one root directory in process structure
  - Implementation special-cases / (always) & `..` in root directory
  - `chroot` does not alway change current directory
  - So chrooting to a lower directory puts you above your new root (Can re-chroot to real system root)
- **What else can you do as root in a chrooted process?**

Escaping chroot

- **Re-chroot to a lower directory, then chroot `../../..`**
  - Each process has one root directory in process structure
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  - `chroot` does not alway change current directory
  - So chrooting to a lower directory puts you above your new root (Can re-chroot to real system root)
- **Create devices that let you access raw disk**
- **Send signals to or ptrace non-chrooted processes**
- **Create setuid program for non-chrooted processes to run**
- **Bind privileged ports, mess with clock, reboot, etc.**
- **Problem: chroot was not originally intended for security**
  - FreeBSD jail attempts to address the problems
  - Also, Linux cgroups, namespaces allow containers

System call interposition

- **Why not use *ptrace* or other debugging facilities to control untrusted programs?**
- **Almost any “damage” must result from system call**
  - delete files → unlink
  - overwrite files → open/write
  - attack over network → socket/bind/connect/send/recv
  - leak private data → open/read/socket/connect/write …
- **So enforce policy by allowing/disallowing each syscall**
  - Theoretically much more fine-grained than chroot
  - Plus don’t need to be root to do it
- **Q: Why is this not a panacea?**

Limitations of syscall interposition

- **Hard to know exact implications of a system call**
  - Too much context not available outside of kernel (e.g., what does this file descriptor number mean?)
  - Context-dependent (e.g., `/proc/self/cwd`)
- **Indirect paths to resources**
  - File descriptor passing, core dumps, “unhelpful processes”
- **Race conditions**
  - Remember difficulty of eliminating TOCCTOU bugs?
  - Now imagine malicious application deliberately doing this
  - Symlinks, directory renames (so “..” changes), …
- **See [Garfinkel] for a more detailed discussion**

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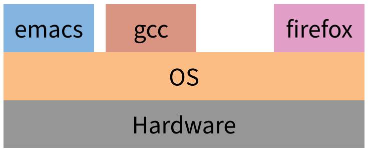
Review: What is an OS



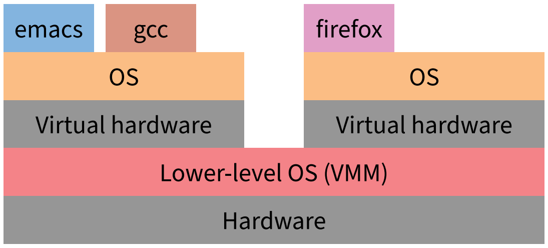
emacs gcc firefox

OS

Hardware

- **OS is software between applications and hardware/external reality**
  - Abstracts hardware to makes applications portable
  - Makes finite resources (memory, # CPU cores) appear much larger
  - Protects processes and users from one another

What if…



emacs gcc firefox

OS OS

Virtual hardware Virtual hardware

Lower-level OS (VMM)

Hardware

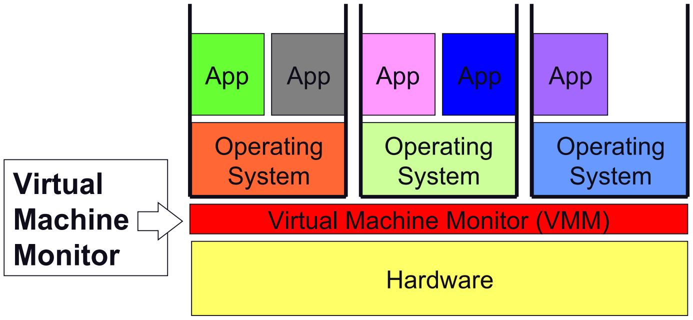
- **The process abstraction looked just like hardware?**

How do process abstraction & HW differ?

Process	**Hardware**
Non-privileged registers and instructions	All registers and instructions
Virtual memory	Both virtual and physical memory, MMU functions, TLB/page tables, etc.
Errors, signals	Trap architecture, interrupts
File system, directories, files, raw devices	I/O devices accessed using programmed I/O, DMA, interrupts

Virtual Machine Monitor

- **Thin layer of software that virtualizes the hardware**
  - Exports a virtual machine abstraction that looks like the hardware



Old idea from the 1960s

- **See [Goldberg] from 1974**
- **IBM VM/370 – A VMM for IBM mainframe**
  - Multiplex multiple OS environments on expensive hardware
  - Desirable when few machines around
- **Interest died out in the 1980s and 1990s**
  - Hardware got cheap
  - Just put a windows machine on every desktop
- **Today, VMs are used everywhere**
  - Used to solve different problems (software management)
  - But VMM attributes more relevant now than ever

VMM benefits

- **Software compatibility**
  - VMMs can run pretty much all software
- **Can get low overheads/high performance**
  - Near "raw" machine performance for many workloads
  - With tricks can have direct execution on CPU/MMU
- **Isolation**
  - *Seemingly* total data isolation between virtual machines (complicated by side-channel attacks like Spectre)
  - Leverage hardware memory protection mechanisms
- **Encapsulation**
  - Virtual machines are not tied to physical machines
  - Checkpoint/migration

OS backwards compatibility

- **Backward compatibility is bane of new OSes**
  - Huge effort require to innovate but not break
- **Security considerations may make it impossible**
  - Choice: Close security hole and break apps or be insecure
- **Example: Windows XP is end of life**
  - 4.59% machines ran 2001 Windows XP in 2018
  - XP support ended in 2019, eventually XP-capable hardware will die
  - What to do with legacy WinXP applications?
  - Not all applications will run on later Windows
  - Given the number of WinXP applications, practically any OS change will break something

```
        if (OS == WinXP)...
```

- **Solution: Use a VMM to run both WinXP and Win10**
  - Obvious for OS migration as well: Windows → Linux

Logical partitioning of servers

- **Run multiple servers on same box (e.g., Amazon EC2)**
  - Modern CPUs more powerful than most services need
  - VMs let you give away less than one machine
  - Server consolidation trend: *N* machines → 1 real machine
  - 0.10U rack space machine – less power, cooling, space, etc.
- **Isolation of environments**
  - Printer server doesn't take down Exchange server
  - Compromise of one VM can't get at data of others[1]
- **Resource management**
  - Provide service-level agreements
- **Heterogeneous environments**
  - Linux, FreeBSD, Windows, etc.

[1] In practice not so simple because of side channels [Ristenpart] [Meltdown]

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Complete Machine Simulation

- Simplest VMM approach, used by `bochs`
- Build a simulation of all the hardware
  - CPU – A loop that fetches each instruction, decodes it, simulates its effect on the machine state
  - Memory – Physical memory is just an array, simulate the MMU on all memory accesses
  - I/O – Simulate I/O devices, programmed I/O, DMA, interrupts
- Problem: Too slow!
  - CPU/Memory – 100x CPU/MMU simulation
  - I/O Device – $< 2\times$ slowdown.
  - 100× slowdown makes it not too useful
- Need faster ways of emulating CPU/MMU

Virtualizing the CPU

- Observations: Most instructions are the same regardless of processor privileged level
  - Example: `incl %eax`
- Why not just give instructions to CPU to execute?
  - One issue: Safety – How to get the CPU back? Or stop it from stepping on us? How about `cli`/`halt`?
  - Solution: Use protection mechanisms already in CPU
- Run virtual machine's OS directly on CPU in unprivileged user mode
  - "Trap and emulate" approach
  - Most instructions just work
  - Privileged instructions trap into monitor and run simulator on instruction
  - Makes some assumptions about architecture

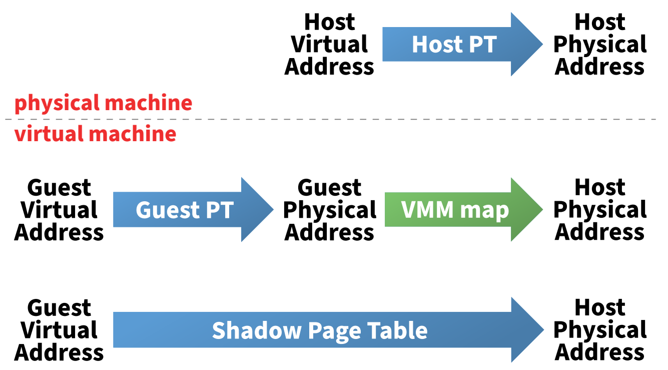
Virtualizing traps

- What happens when an interrupt or trap occurs
  - Like normal kernels: we trap into the monitor
- What if the interrupt or trap should go to guest OS?
  - Example: Page fault, illegal instruction, system call, interrupt
  - Re-start the guest OS simulating the trap
- x86 example:
  - Give CPU an IDT that vectors back to VMM
  - Look up trap vector in VM's "virtual" IDT
  - Push virtualized `%cs`, `%eip`, `%eflags`, on stack
  - Switch to virtualized privileged mode

Virtualizing memory

- Basic MMU functionality:
  - OS manages physical memory (0...MAX_MEM)
  - OS sets up page tables mapping VA ⟶ PA
  - CPU accesses to VA should go to PA (if paging off, PA = VA)
  - Used for every instruction fetch, load, or store
- Need to implement a virtual "physical memory"
  - Logically need additional level of indirection
  - VM's *Guest VA* ⟶ VM's *Guest PA* ⟶ *Host PA*
  - Note "Guest physical" memory no longer means hardware bits
  - Hardware is host physical memory (a.k.a. machine memory)
- Trick: Use hardware MMU to simulate virtual MMU
  - Point hardware at *shadow page table*
  - Directly maps Guest VA ⟶ Host PA

Memory mapping summary



Host Virtual Address → Host PT → Host Physical Address

physical machine

virtual machine

Guest Virtual Address → Guest PT → Guest Physical Address → VMM map → Host Physical Address

Guest Virtual Address → Shadow Page Table → Host Physical Address

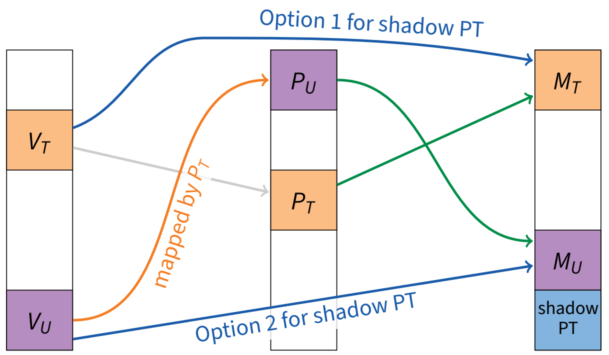
Shadow page tables

- VMM responsible for maintaining *shadow* PT
  - And for maintaining its consistency (including TLB flushes)
- Shadow page tables are a cache
  - Have *true page faults* when page not in VM's guest page table
  - Have *hidden page faults* when just misses in shadow page table
- On a page fault, VMM must:
  - Lookup guest VPN ⟶ guest PPN in guest's page table
  - Determine where guest PPN is in host physical memory
  - Insert guest VPN ⟶ host PPN mapping in shadow page table
  - Note: VMM can demand-page the virtual machine
- Uses hardware protection

Shadow PT issues

- **Hardware only ever sees shadow page table**
  - Guest OS only sees it's own VM page table, never shadow PT
- **Consider the following**
  - Guest OS has a page table T mapping $V_U \rightarrow P_U$
  - T itself resides at guest physical address P_T
  - Another guest page table entry maps $V_T \rightarrow P_T$ (e.g., in Pintos, $V_T = P_T + \texttt{PHYS\_BASE}$)
  - VMM stores P_U in host physical address M_U and P_T in M_T
- **What can VMM put in shadow page table?**
  - Safe to map user page ($V_U \longrightarrow M_U$) *or* page table ($V_T \longrightarrow M_T$)
- **Not safe to map both simultaneously!**
  - If OS writes to P_T, may make $V_U \longrightarrow M_U$ in shadow PT incorrect
  - If OS reads/writes V_U, may require accessed/dirty bits to be changed in P_T (hardware can only change shadow PT)

Illustration



- **Option 1:** Page table accessible at V_T, but changes won't be reflected in shadow PT or TLB; access to V_U dangerous
- **Option 2:** V_U accessible, but hardware sets accessed/dirty bits only in shadow PT, not in guest PT at P_T/M_T

Tracing

- **VMM needs to get control on some memory accesses**
- **Guest OS changes previously used mapping in its PT**
  - Must intercept to invalidate stale mappings in shadow PT, TLB
  - Note: OS *should* use `invlpg` instruction, which would trap to VMM – but in practice many/most OSes are sloppy about this
- **Guest OS accesses page when its VM PT is accessible**
  - Accessed/dirty bits in VM PT may no longer be correct
  - Must intercept to fix up VM PT (or make VM PT inaccessible)
- **Solution: *Tracing***
  - To track page access, make VPN(s) invalid in shadow PT
  - If guest OS accesses page, will trap to VMM w. page fault
  - VMM can emulate the result of memory access & restart guest OS, just as an OS restarts a process after a page fault

Tracing vs. hidden faults

- **Suppose VMM never allowed access to VM PTs?**
  - Every PTE access would incur the cost of a tracing fault
  - Very expensive when OS changes lots of PTEs
- **Suppose OS allowed access to *most* page tables (except very recently accessed regions)**
  - Now lots of hidden faults when accessing new region
  - Plus overhead to pre-compute accessed/dirty bits from shadow PT as page tables preemptively made valid in shadow PT
- **Makes for complex trade-offs**
  - But adaptive binary translation (later) can make this better

I/O device virtualization

- **Types of communication**
  - Special instruction – `in`/`out`
  - Memory-mapped I/O (PIO)
  - Interrupts
  - DMA
- **Make `in`/`out` and PIO trap into monitor**
- **Use tracing for memory-mapped I/O**
- **Run simulation of I/O device**
  - Interrupt – Tell CPU simulator to generate interrupt
  - DMA – Copy data to/from physical memory of virtual machine

CPU virtualization requirements

- **Need protection levels to run VMs and monitors**
- **All unsafe/privileged operations should trap**
  - Example: disable interrupt, access I/O dev, ...
  - x86 problem: `popfl` (different semantics in different rings)
- **Privilege level should not be visible to software**
  - Software shouldn't be able to query and find out it's in a VM
  - x86 problem: `movw %cs, %ax`
- **Trap should be transparent to software in VM**
  - Software in VM shouldn't be able to tell if instruction trapped
  - x86 problem: traps can destroy machine state (E.g., if internal segment register was out of sync with GDT)
- **See [Goldberg] for a discussion**

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Binary translation

- **Cannot directly execute guest OS kernel code on x86**
  - Can maybe execute most user code directly
  - But how to get good performance on kernel code?
- **Original VMware solution: binary translation**
  - Don't run slow instruction-by-instruction emulator
  - Instead, translate guest kernel code into code that runs in fully-privileged kernel mode, but acts safely[2]
- **Challenges:**
  - Don't know the difference between code and data (guest OS might include self-modifying code)
  - Translated code may not be the same size as original
  - Prevent translated code from messing with VMM memory
  - Performance, performance, performance, . . .

[2] actually CPL 1, so that the VMM has its own exception stack

VMware binary translator

- **VMware translates kernel dynamically (like a JIT)**
  - Start at guest `eip`
  - Accumulate up to 12 instructions until next control transfer
  - Translate into binary code that can run in VMM context
- **Most instructions translated identically**
  - E.g., regular `movl` instructions
- **Use segmentation to protect VMM memory**
  - VMM located in high virtual addresses
  - Segment registers "truncated" to block access to high VAs
  - `gs` segment not truncated; use it to access VMM data
  - Any guest use of `gs` (rare) can't be identically translated

Details/examples from [Adams & Agesen]

Control transfer

- **All branches/jumps require indirection**
- **Original:**

```
isPrime: mov %edi, %ecx # %ecx = %edi (a)
         mov $2, %esi   # i = 2
         cmp %ecx, %esi # is i >= a?
         jge prime      # jump if yes
         ...
```

- **C source:**

```
int
isPrime (int a)
{
  for (int i = 2; i < a; i++) {
    if (a % i == 0)
      return 0;
  }
  return 1;
}
```

Control transfer

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```
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         jge prime      # jump if yes
         ...
```

- **Translated:**

```
isPrime': mov %edi, %ecx   # IDENT
          mov $2, %esi
          cmp %ecx, %esi
          jge [takenAddr]  # JCC
          jmp [fallthrAddr]
```

- **Brackets ([. . .]) indicate *continuations***
  - First time jumped to, target untranslated; translate on demand
  - Then fix up continuation to branch to translated code
  - Can elide `[fallthrAddr]` if fallthrough next translated

Non-identically translated code

- **PC-relative branches & Direct control flow**
  - Just compensate for output address of translator on target
  - Insignificant overhead
- **Indirect control flow**
  - E.g., jump though register (function pointer) or `ret`
  - Can't assume code is "normal" (e.g., must faithfully `ret` even if stack doesn't have return address)
  - Look up target address in hash table to see if already translated
  - "Single-digit percentage" overhead
- **Privileged instructions**
  - Appropriately modify VMM state
  - E.g., `cli` ⟹ `vcpu.flags.IF = 0`
  - Can be faster than original!

Adaptive binary translation

- **One remaining source of overhead is tracing faults**
  - E.g., when modifying page table or descriptor table
- **Idea: Use binary translation to speed up**
  - E.g., translate write of PTE into write of guest & shadow PTE
  - Translate read of PTE to get accessed & dirty bits from shadow
- **Problem: Which instructions to translate?**
- **Solution: “innocent until proven guilty” model**
  - Initially always translate as much code identically as possible
  - Track number of tracing faults caused by an instruction
  - If high number, re-translate to non-identical code
  - May call out to interpreter, or just jump to new code

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Hardware-assisted virtualization

- **Both Intel and AMD now have hardware support**
  - Different mechanisms, similar concepts
  - This lecture covers AMD (see [AMD Vol 2], Ch. 15)
  - For Intel details, see [Intel Vol 3c]
- **VM-enabled CPUs support new *guest* mode**
  - This is separate from kernel/user modes in bits 0–1 of `%cs`
  - Less privileged than *host* mode (where VMM runs)
  - Some sensitive instructions trap in guest mode (e.g., load `%cr3`)
  - Hardware keeps shadow state for many things (e.g., `%eflags`)
- **Enter guest mode with `vmrun` instruction**
  - Loads state from hardware-defined 1-KiB VMCB data structure
- **Various events cause EXIT back to host mode**
  - On EXIT, hardware saves state back to VMCB

VMCB control bits

- ***Intercept vector* specifies what ops should cause EXIT**
  - One bit for each of `%cr0`–`%cr15` to say trap on read
  - One bit for each of `%cr0`–`%cr15` to say trap on write
  - 32 analogous bits for the debug registers (`%dr0`–`%dr15`)
  - 32 bits for whether to intercept exception vectors 0–31
  - Bits for various other events (e.g., NMI, SMI, ...)
  - Bit to intercept writes to sensitive bits of `%cr0`
  - 8 bits to intercept reads and writes of IDTR, GDTR, LDTR, TR
  - Bits to intercept `rdtsc`, `rdpmc`, `pushf`, `popf`, `vmrun`, `hlt`, `invlpg`, `int`, `iret`, `in`/`out` (to selected ports), . . .
- **EXIT code and reason (e.g., which inst. caused EXIT)**
- **Other control values**
  - Pending virtual interrupt, event/exception injection

Guest state saved in VMCB

- **Saved guest state**
  - Full segment registers (i.e., base, lim, attr, not just selectors)
  - Full GDTR, LDTR, IDTR, TR
  - Guest `%cr3`, `%cr2`, and other cr/dr registers
  - Guest `%eip` and `%eflags` (`%rip` & `%rflags` for 64-bit processors)
  - Guest `%rax` register
- **Entering/exiting VMM more expensive than syscall**
  - Have to save and restore large VM-state structure

Hardware vs. Software virtualization

- **HW VM makes implementing VMM much easier**
  - Avoids implementing binary translation (BT)
- **Hardware VM is better at entering/exiting kernel**
  - E.g., Apache on Windows benchmark: one address space, lots of syscalls, hardware VM does better [Adams]
  - Apache on Linux w. many address spaces: lots of context switches, tracing faults, etc., Software faster [Adams]
- **Fork with copy-on-write bad for both HW & BT**
  - [Adams] reports fork benchmark where BT-based virtualization 37× and HW-based 106× slower than native!
- **Today, CPUs support *nested paging* (a.k.a. EPT on intel)**
  - Eliminates shadow PT & tracing faults, simplifies VMM
  - Guests can now manipulate `%cr3` w/o VM EXIT
  - But dramatically increases cost of TLB misses

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ESX memory management [Waldspurger]

- **Virtual machines see virtualized physical memory**
  - Can let VMs use more "physical" memory than in machine
- **How to apportion memory between machines?**
- **VMware ESX has three parameters per VM:**
  - min – Don't bother running w/o this much machine memory
  - max – Amount of guest physical memory VM OS thinks exists
  - share – How much memory to give VM relative to other VMs
- **Straw man: Allocate based on share, use LRU paging**
  - OS already uses LRU $\Longrightarrow$ double paging
  - OS will re-cycle whatever "physical" page VMM just paged out
  - So better to do random eviction
- **Next: 3 cool memory management tricks**

Reclaiming pages

- **Normally OS just uses all available memory**
  - But some memory much more important than other memory
  - E.g., buffer cache may contain old, clean buffers; OS won't discard if doesn't need memory… but VMM may need memory
- **Idea: Have guest OS return memory to VMM**
  - Then VMM doesn't have to page memory to disk
- **ESX trick: Balloon driver**
  - Special pseudo-device driver in supported guest OS kernels
  - Communicates with VMM through special interface
  - When VMM needs memory, allocates many pages in guest OS
  - Balloon driver tells VMM to re-cycle its private pages

Sharing pages across VMs

- **Often run many VMs with same OS, programs**
  - Will result in many host physical pages containing same data
- **Idea: Use 1 host physical page for all copies of guest physical page (in any virtual machine)**
- **Keep big hash table mapping:** Hash(contents)→info
  - If host physical page mapped once, info is VM/PPN where mapped.
    In that case, Hash is only a hint, as page may have changed
  - If machine page mapped copy-on-write as multiple physical pages, info is just reference count
- **Scan OS pages randomly to populate hash table**
- **Always try sharing a page before paging it out**

Idle memory tax

- **Need machine page? What VM to take it from?**
- **Normal proportional share scheme**
  - Reclaim from VM with lowest "shares-to-pages" (S/P) ratio
  - If A & B both have $S = 1$, reclaim from larger VM
  - If A has twice B's share, can use twice the machine memory
- **High-priority VMs might get more memory than needed**
- **Solution: Idle-memory tax**
  - Use statistical sampling to determine a VM's % idle memory (randomly invalidate pages & count the number faulted back)
  - Instead of S/P, reclaim from VM with lowest $S/(P(f + k(1 - f)))$.
    f = fraction of non-idle pages; k = "idle page cost" paremeter.
  - Be conservative & overestimate f to respect priorities
    (f is max of slow, fast, and recent memory usage samples)